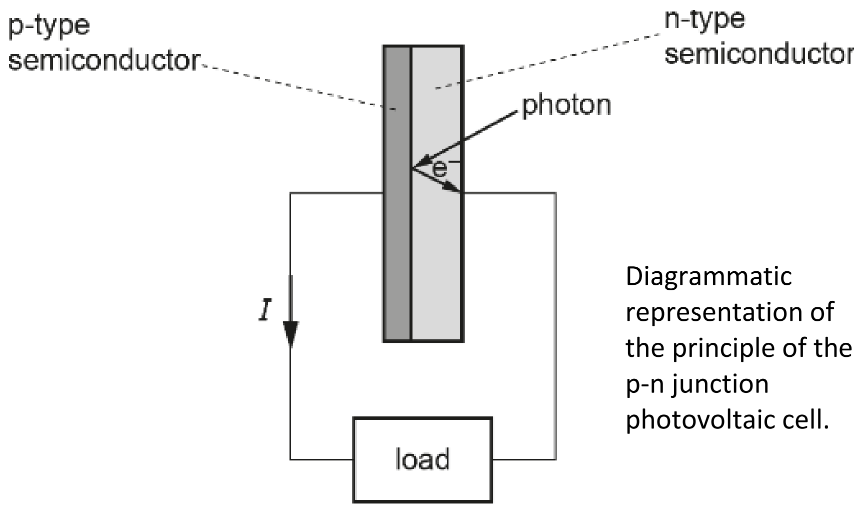
A **Level** Physics B H557/02 - Advance Notice Article 2018

Flying on sunshine

Having left the Earth nearly five years earlier, the space probe Juno entered orbit around Jupiter on July 4, 2016. A little over three weeks later, on July 26, the aeroplane Solar Impulse 2 landed in Abu Dhabi having flown around the world in a number of stages. Juno and Solar Impulse 2, both record-breakers, share a common power source – the Sun. Juno has travelled further from the Sun than any previous solar-powered probe and Solar Impulse 2 is the first solar-powered aeroplane to circle the globe. These achievements show that there is much more to solar cells than simply units for recharging batteries to power calculators or LED garden lights. Banks of solar cells are increasingly seen on the roofs of houses, factories and schools and missions such as Juno and Solar Impulse 2 help push forward the technology of solar power, improving its efficiency and making sunshine an increasingly attractive source of energy.

Photovoltaic cells

When light of sufficiently high frequency strikes a metal surface, photoelectrons are released. This is the photoelectric effect, explained by Einstein in 1905. In modern terminology, a photon transfers its energy to an individual electron which, if the energy of the photon is great enough, will escape the surface of the metal.



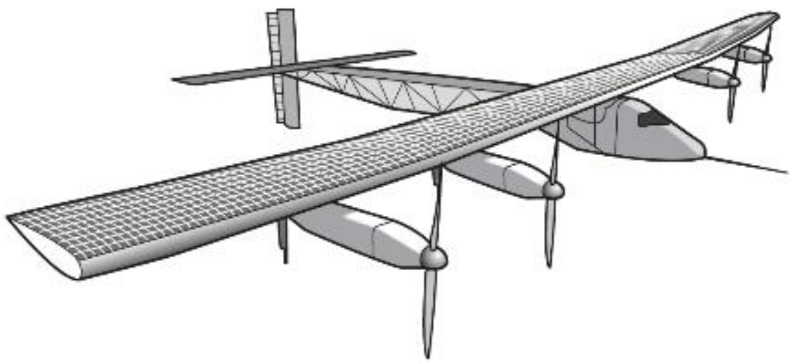
Diagrammatic representation of the principle of the p-n junction photovoltaic cell.

Photovoltaic cells (or solar cells) also rely on the transfer of energy from a photon to an electron. In this case, photons strike electrons within a semiconductor arrangement known as a p-n junction, a p-type semiconductor joined to an n-type semiconductor. The details of the physics of the junction are beyond the scope of this article. If photons striking the cell have sufficient energy, electrons will be promoted into the 'n' region. This sets up an e.m.f. which can drive a current through a load. If the wavelength of light falling on the semiconductor is too long there will be no e.m.f. generated.

The photovoltaic cell is a slice of p-n material. Its upper surface (the top of the n-type layer) has a grid of wires to collect the electrons which pass through the load and then back to the p-type layer. The upper surface can also be given a non-reflective coating to increase the efficiency of the cell. An individual cell can produce an e.m.f. of about 0.5 V. Combining a number of cells in series increases the e.m.f. of the system. Typically, a number of cells are combined in a module which produces an e.m.f. of 12 V. Such modules can be combined to produce e.m.f.s and currents suitable for a range of applications. In nearly all cases, the cells are used to recharge batteries to provide a constant source of power independent of light levels.

Solar Impulse 2

A solar-powered aircraft needs to be light and have a large surface area of wing for gliding and to provide a surface for the solar cells. The skin of the wings is supported by an internal frame made from carbon fibre which is low density, stiff and strong. The plane does not fly at a constant height; during daylight, when there is sufficient light to power the motors and recharge the batteries, it rises to a height of 8500 m. At night it glides down to a height of about 1500 m over a period of 4 hours. After this, the motors are powered by the batteries until the cycle repeats the next day.



Solar Impulse 2 Data
Number of solar cells: 17 000
Total area of solar cells: 270 m^2
Mass of batteries: 630 kg
Energy storage in batteries: 9.4×10^5 J kg^{-1}
Total mass of plane: 2300 kg
Efficiency of solar cells: 23%
Wingspan: 72 m

Juno

The Atlas V rocket that launched Juno did not give the spacecraft sufficient energy to climb the gravitational potential well from Earth to Jupiter. To gain more energy, after orbiting the Sun for two years, Juno swung past the Earth, picked up kinetic energy from the planet and headed out for Jupiter. This is a process known as a gravitational slingshot. Simplifying the situation greatly, imagine the situation shown in Fig. 3, where V_S is the velocity of the spacecraft relative to the Sun and V_E is the velocity of the Earth relative to the Sun.

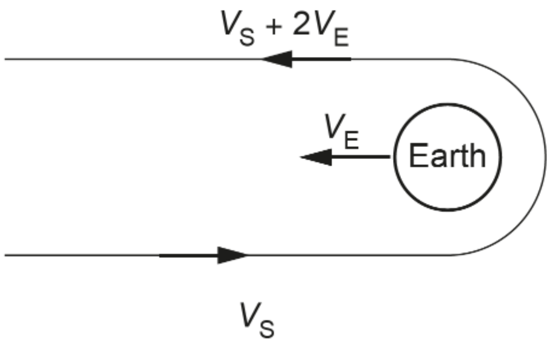
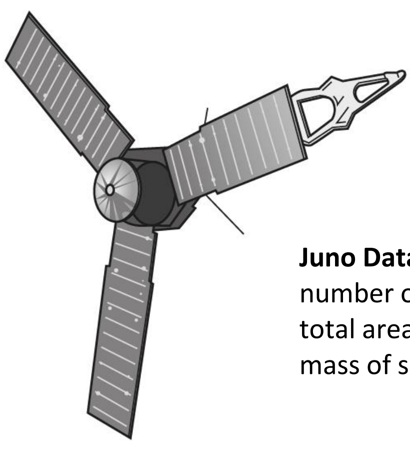


Fig. 3 Velocities of approach and recession of spacecraft to Earth, relative to the Sun.

From the point of view of an observer on the Earth, the spacecraft approaches at velocity $V_S + V_E$. The spacecraft swings past the Earth and leaves at the same speed relative to the Earth that it approached. But relative to the Sun things look rather different; its initial velocity is V_S and when the spacecraft is travelling away with a velocity $V_S + V_E$ relative to the Earth it will be travelling relative to the Sun at velocity $(V_S + V_E) + V_E = V_S + 2V_E$. Of course, spacecraft do not make head-on approaches to planets in this manner but this simplification shows the basic principle. When Juno performed the slingshot manoeuvre with the Earth, it increased its speed from 3.5×10^4 m s^{-1} to 4.2×10^4 m s^{-1}.

The intensity of solar radiation follows an inverse-square relationship with distance from the Sun. Jupiter is 5.2 astronomical units (AU) from the Sun; in other words, 5.2 times further from the Sun than the Earth is. The solar panels on Juno need to be as large and efficient as practicable. Powered only by the Sun, Juno will orbit Jupiter while sending valuable scientific data back to Earth. It is expected to make about 50 orbits of the planet until its instruments and solar cells are too damaged by radiation to be of further use and the spacecraft will be directed to fall towards Jupiter, burning up in the atmosphere of the giant planet. Juno and Solar Impulse 2 show that solar cells have a bright future – even in the darker reaches of the Solar System.



Juno Data
number of solar cells: 19 000
total area of solar cells: 60 m^2
mass of spacecraft: 3600 kg

Flying on Sunshine Questions

1 The Sun emits light with a peak wavelength of around 500nm.
   a) Calculate the frequency.
   b) Calculate the photon energy in Joules.
   c) Calculate the photon energy in eV.

2 A photovoltaic cell can produce an e.m.f. of 0.5V.
   a) What energy is supplied to each electron by each photon in eV?
   b) Calculate the energy supplied to each electron in Joules.
   c) Calculate the maximum wavelength of light that the photovoltaic cell can make use of.
   d) Explain why light with a longer wavelength will produce no e.m.f from the cell.

3 Carbon fibre, used in Solar Impulse's wings is low density, stiff and strong.
Explain the meaning of the terms **and** suggest why each property is desirable.
Include the terms Young modulus and yield stress in your explanations.

a) low density b) stiff c) strong

4 Use the **Solar Impulse 2 Data** and data in the text to calculate:
   a) The length of the sides of the solar cells (assuming they are square).
   b) The energy that can be stored in the batteries.
   c) The mean width of the wings.
   d) The gravitational potential energy lost during the 4 hour glide.
   e) The power at which GPE is lost during the glide.
   f) Make a sensible estimate as to the power required to keep the plane aloft.
   g) Calculate the solar energy input required to supply this power.
   h) Calculate an estimate of the solar radiation flux in Wm^{-2}.
   i) Calculate the time required to fully charge the storage batteries.

5 Juno uses a gravitational slingshot to increase its velocity.
   a) Calculate the kinetic energy gained by Juno.
   b) Explain the source of this energy.
   c) Calculate the change in momentum of Juno.
   d) Explain how the total momentum is conserved.
   e) The slingshot took around 9 hours. Calculate the mean gravitational force on Juno.

6 Light intensity follows in inverse square law.
   a) Calculate what fraction of the Earth's solar flux that Juno receives.
   b) Calculate power supplied by the solar cells assuming an efficiency of 35%

7 Juno will orbit Jupiter, which has a mass of 1.9×10^{27} kg, once every 14 Earth days.
   a) Calculate the orbital period in seconds.
   b) Use the equations for centripetal acceleration and gravitational force and the data above to **show that** the average radius of Juno's orbit around Jupiter is about 1.7 million kilometres.
   c) Calculate the velocity of Juno in its orbit around Jupiter.
   d) Jupiter has a diameter of 143000 km. Calculate the speed that Juno will enter the top of Jupiter's atmosphere.

Flying on Sunshine Questions

1 The Sun emits light with a peak wavelength of around 500nm.

a) Calculate the frequency.

$f = c/\lambda = 3.0 \times 10^8 / 500 \times 10^{-9} = \underline{6.0 \times 10^{14}\ \text{Hz}}$

b) Calculate the photon energy in Joules.

$E=hf = 6.6 \times 10^{-34} \times 6.0 \times 10^{14} = \underline{3.96 \times 10^{-19}\ \text{J}}$

c) Calculate the photon energy in eV.

There are 1.6×10^{-19} J/eV $\therefore E = 3.96 \times 10^{-19}\ \text{J} / 1.6 \times 10^{-19}\ \text{J/eV} = \underline{2.48\ \text{eV}}$

2 A photovoltaic cell can produce an e.m.f. of 0.5V.

a) What energy is supplied to each electron by each photon in eV?

The definition of the eV is the energy transferred per electron per volt so = 0.5eV

b) Calculate the energy supplied to each electron in Joules.

$E = QV = 1.6 \times 10^{-19} \times 0.5 = \underline{8.0 \times 10^{-20}\ \text{J}}$

c) Calculate the maximum wavelength of light that the photovoltaic cell can make use of.

$E = hc/\lambda \therefore \lambda = hc/E = 6.6 \times 10^{-34} \times 3.0 \times 10^8 / 8.0 \times 10^{-20} = 2.48 \times 10^{-6}\ \text{m} = \underline{2480\ \text{nm}}$

d) Explain why light with a longer wavelength will produce no e.m.f from the cell.

Each individual photon has less energy than is required to promote an electron to a higher energy level.

3 Carbon fibre, used in Solar Impulse's wings is low density, stiff and strong.
Explain the meaning of the terms **and** suggest why each property is desirable.
Include the terms Young modulus and yield stress in your explanations.

a) low density density = mass / volume. It is a measure of the amount of matter per unit volume. Low density is desirable because the mass of the plane will be lower. It will therefore require less lift for steady flight reducing the power and hence energy needed for flight.

b) stiff Stiffness is the opposite of flexibility. A stiff material means less can be used to make the winds stiff enough to withstand the forces involved in flight. Less material means the lighter wings. Stiffness can be quantified in terms of the Young modulus which is stress / strain.

c) strong A strong material has a high yield stress. It can withstand a high force/ cross sectional area ratio before yield, and hence, plastic deformation occurs. Wings need to be strong as they must support the weight of the plane and the drag produced by air resistance.

4 Use the **Solar Impulse 2 Data** and data in the text to calculate:

a) The length of the sides of the solar cells (assuming they are square).

area = length of sides^2 $\therefore$ length of side $= \sqrt{\text{area}} = \sqrt{270\text{m}^2} = \underline{16.4\ \text{m}}$

b) The energy that can be stored in the batteries.

energy = energy density x mass $= 9.4 \times 10^5\ \text{Jkg}^{-1} \times 630\ \text{kg} = \underline{5.9 \times 10^8\ \text{J}}$

c) The mean width of the wings.

area = length × width $\therefore$ width = area / length $= 270\ \text{m}^2 / 72\text{m} = \underline{3.75\ \text{m}}$

d) The gravitational potential energy lost during the 4 hour glide.

$\Delta E_{grav} = mg\Delta h = 2300\ \text{kg} \times 9.81 \times (8500\ \text{m} - 1500\ \text{m}) = \underline{1.58 \times 10^8\ \text{J}}$

e) The power at which GPE is lost during the glide.

$P = E/t = 1.58 \times 10^8\ \text{J} / (4 \times 60 \times 60) = 1.10 \times 10^4\ \text{W} = \underline{11\ \text{kW}}$

f) Make a sensible estimate as to the power required to keep the plane aloft.

It must be around the same power as the glide down. Say 10 kW.

g) Calculate the solar energy input required to supply this power.

electricity out = 0.23 x solar input $\therefore$ solar input = electricity out / 0.23 $= 1 \times 10^4 / 0.23 = \underline{4.3 \times 10^4\ \text{W}}$

h) Calculate an estimate of the solar radiation flux in Wm^{-2}.

flux = power / area $= 4.3 \times 10^4\ \text{W} / 270\ \text{m}^2 = \underline{160\ \text{Wm}^{-2}}$

i) Calculate the time required to fully charge the storage batteries.

$P = E/t \therefore t = E/P = 5.9 \times 10^8\ \text{J} / 11\ \text{kW} = 5.36 \times 10^4\ \text{s} = \underline{14.9\ \text{hours}}$

5 Juno uses a gravitational slingshot to increase its velocity.

a) Calculate the kinetic energy gained by Juno.

$\Delta E_k = 0.5 \times m\Delta v^2 = 0.5 \times 3600 \times (4.2 \times 10^4 - 3.5 \times 10^4)^2 = \underline{8.82 \times 10^{10}\ J}$

b) Explain the source of this energy.

The Earth (It will have lost this amount of kinetic energy)

c) Calculate the change in momentum of Juno.

$\Delta p = m\Delta v = 3600 \times (4.2 \times 10^4 - 3.5 \times 10^4) = \underline{2.52 \times 10^7\ kgms^{-1}}$

d) Explain how the total momentum is conserved.

The Earth will have lost the same amount of momentum as its orbital velocity is reduced.

e) The slingshot took around 9 hours. Calculate the mean gravitational force on Juno.

$F = \Delta mv/\Delta t = 3600 \times (4.2 \times 10^4 - 3.5 \times 10^4) / (9 \times 60 \times 60) = \underline{780\ N}$

6 Light intensity follows in inverse square law.

a) Calculate what fraction of the Earth's solar flux that Juno receives.

$=1/5.2^2 = 1/27 = \underline{0.0370}$

b) Calculate power supplied by the solar cells assuming an efficiency of 35%

At Earth solar flux $\approx 160\ Wm^{-2}$ (from 4h) $\therefore$ at Jupiter $= 160 \times 0.0370 = \underline{5.92\ Wm^{-2}}$

Area $= 60\ m^2 \therefore$ power $= 60\ m \times 5.92\ Wm^{-2} = \underline{355\ W}$

7 Juno will orbit Jupiter, which has a mass of 1.9×10^{27} kg, once every 14 Earth days.

a) Calculate the orbital period in seconds.

$T = 14 \times 24 \times 60 \times 60 = 1.21 \times 10^6\ s$

b) Use the equations for centripetal acceleration and gravitational force and the data above to **show that** the average radius of Juno's orbit around Jupiter is about 1.7 million kilometres.

$F = mv^2/r$ and $F = GMm/r^2 \therefore mv^2/r = GMm/r^2 \therefore v^2 = GM/r$ & $v = s/t = 2\pi r/T \therefore v^2 = 4\pi^2 r^2/T^2$

Equating the two expressions for v^2 gives: $GM/r = 4\pi^2 r^2/T^2$ which rearranges to $r^3 = GMT^2/4\pi^2$

$r^3 = 6.67 \times 10^{-11} \times 1.9 \times 10^{27} \times (1.21 \times 10^6)^2 = 4.79 \times 10^{27}\ m^3 \therefore r = \sqrt[3]{4.79 \times 10^{27}} = \underline{1.68 \times 10^9\ m}$

c) Calculate the velocity of Juno in its orbit around Jupiter.

$v = 2\pi r/T = 2\pi \times 1.68 \times 10^9\ m / 1.21 \times 10^6\ s = 8.72 \times 10^3\ ms^{-1}$

d) Jupiter has a diameter of 143000 km. Calculate the speed that Juno will enter the top of Jupiter's atmosphere.

ΔE_{grav} will be converted to ΔE_k as Juno falls giving it additional velocity.

In orbit $E_{grav} = -GMm/r_{orbit} = -6.67 \times 10^{-11} \times 1.9 \times 10^{27} \times 3600 / 1.68 \times 10^9 = -2.72 \times 10^{11}\ J$

At top of atmos $E_{grav} = -GMm/r_{atmos} = -6.67 \times 10^{-11} \times 1.9 \times 10^{27} \times 3600 / 1.43 \times 10^8 = -3.19 \times 10^{12}\ J$

$\Delta E_k = -\Delta E_{grav} = -(-3.19 \times 10^{12} - -2.72 \times 10^{11}) = 2.92 \times 10^{12}\ J$

$\Delta E_k = m\Delta v^2/2 \therefore \Delta v = \sqrt{(2\Delta E_k/m)} = \sqrt{(2 \times 2.92 \times 10^{12} / 3600)} = 4.03 \times 10^4\ ms^{-1}$

Final velocity = initial + $\Delta v = 8.72 \times 10^3 + 4.03 \times 10^4 = \underline{4.9 \times 10^4\ ms^{-1}}$